Chemical Composition of Large Lakes in Alaska's Arctic Network

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Natural Resource Data Series NPS/ARCN/NRDS—2015/985

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November 2015

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Please cite this publication as:

O'Donnell, J. A., G. R. Aiken, K. D. Butler, and T. A. Douglas. 2015. Chemical composition of large lakes in Alaska's Arctic Network: 2013-2014. Natural Resource Data Series NPS/ARCN/NRDS—2015/985. National Park Service, Fort Collins, Colorado.

Contents

Figures

Figures (continued)

Tables

Abstract

The chemical composition of lakes is an important ecosystem property that can have considerable influence on aquatic ecosystem structure and function. Since lake chemistry is sensitive to climate and disturbance, lakes may serve as a sentinel of climate change through long-term monitoring. Here, we report findings from a two-year pilot study aimed at characterizing the chemical composition of large lakes in National Park Service lands of the Arctic Inventory and Monitoring Network (ARCN). We collected water samples from 20 large lakes in Bering Land Bridge National Preserve (BELA), Gates of the Arctic National Park (GAAR), and Noatak National Preserve (NOAT) during the 2013 and 2014 field seasons (between June and September). Water samples were analyzed for dissolved organic matter (DOM) composition, nutrient concentrations, major cations and anions, and water stable isotopes. We also collected field measurements of lake surface temperature and temperature profiles, specific conductivity, and pH. We observed considerable variation in the chemical composition of large lakes in the ARCN parks. For instance, DOC concentrations ranged from 1 to 12 $mgC\ L^{-1}$ across all lakes, and DOM aromaticity was highly variable, as indicated by measurements of specific ultraviolet absorbance ($SUVA_{254}$). Nutrient concentrations (nitrogen and phosphorus species) were generally low, indicating oligotrophic conditions and likely strong nutrient-limitation of primary production. Cation and anion concentrations varied across lakes, reflecting spatial variations in lithology. Overall, large lakes appear to be unimpaired with respect to a broad suite of water quality parameters. However, Arctic lakes are likely vulnerable to climate-driven changes hydrology and landscape disturbance (e.g. wildfire and permafrost thaw). Future monitoring of large lakes ARCN should be designed to detect chemical and hydrologic properties across space and time, both as a means of assessing these vulnerabilities and for improving watershed management activities.

Acknowledgments

We thank Kathryn Motter for facilitating sample analysis at the Cooperative Chemical Analytical Laboratory at Oregon State University. We also thank Dr. David Swanson and Scott Miller for providing helpful comments on an earlier draft of this report.

Introduction

Lake ecosystems are sensitive to climate change, both through the direct effects of temperature on lake structure and function and through the indirect effects of climate change on the surrounding terrestrial landscape. Recent findings in high-latitude regions have documented changes in lake area (Smith *et al*. 2006; Swanson 2013), lake ice dynamics (Arp *et al*. 2013), and lake temperature (Prowse *et al*. 2006). As a result, researchers have viewed lakes as sentinels of climate change (Adrian *et al*. 2009). In addition to changing thermal structure and ice phenology, lake chemistry also can serve as a critical indicator of changing climate. Long-term shifts in the chemical composition of lakes may serve as an indicator of changing terrestrial processes. For instance, changing nutrient concentration or ratios may reflect climate-driven changes in terrestrial net primary production, precipitation or runoff, or disturbance (e.g. fire, erosion). Dissolved organic carbon (DOC) concentration in lakes has also been used as an indicator and integrator of terrestrial ecosystem change (Lapierre *et al*. 2015). Chemical changes can also occur through internal lake processes, such as changes in lake temperature regimes, thermal stratification, or rates of primary production.

A shift in lake chemistry may have important implications for aquatic organisms, greenhouse gas emissions, and ecosystem services. In the Arctic, changes in lake temperature and chemical composition have caused shifts in the biological communities of lakes (Smol *et al*. 2005). Laboratory and field experiments have documented significant nutrient limitation of primary productivity by phytoplankton in Arctic lakes (Levine and Whalen 2001), which is a primary control on invertebrate and fish production in many high-latitude lakes (Hershey 1992). Lake chemistry is also an important control on the emission of greenhouse gases (e.g. carbon dioxide and methane) to the atmosphere (Kling *et al*. 1991; McDonald *et al*. 2013), which can function as a positive feedback to the climate system and account for a significant portion of the high-latitude carbon budget (McGuire *et al*. 2010). Ecosystem services may also be impacted by shifts in lake chemistry. For instance, eutrophication due to increased nutrient loading may reduce water quality and fish productivity, and in turn, negatively affect recreational and subsistence activities (Adrian *et al*. 2009; Carpenter *et al*. 2009).

The aim of the present study is to provide baseline chemical data for large lakes in the Arctic Inventory and Monitoring Network (ARCN). ARCN is comprised of five NPS park units, covering more than 78,000 km^2 in northern Alaska. The area is extremely remote and pristine with almost no road access and minimal anthropogenic impacts. The intent of the program is to assess and track the overall condition of park resources through the monitoring of 19 vital signs (Lawler *et al*. 2009). Herein, we present results from a pilot study conducted in 2013 and 2014 as a component of the Lake Communities and Ecosystems Vital Sign (Burkart 2011) and as counterpart to the Shallow Lakes vital sign (Larsen *et al*. 2011). Data from this study will be used to guide protocol development for long-term monitoring and for selection of intensive and extensive study sites. Overall, our aim is to improve management practices in watersheds of ARCN park units through targeted data collection and interpretation.

Methods

Overview

We sampled 20 large lakes across three of the five National Park Service units of the Arctic Inventory and Monitoring Network (ARCN), including Bering Land Bridge National Preserve (BELA), Gates of the Arctic National Park (GAAR), and Noatak National Preserve (NOAT; Figure 1). BELA samples were collected between June 21-23, 2013. To access field sites in BELA, we traveled via R44 helicopter from Nome, Alaska (Bering Air, Inc). NOAT samples were collected between June 27-28 and September 15-16, 2013. For the first trip in late June, we collected samples using the Denali National Park fire helicopter based out of Kelly River Ranger Station in western NOAT. For the second trip in mid-September, we collected samples using an R44 helicopter contracted through Quicksilver Air. GAAR samples were collected on June 26, 2014 and August 6-8, 2014. For the first trip in late June, we accessed study sites via C-185 floatplane. For the second trip in mid-August, we accessed study sites via R44 helicopter contracted through Quicksilver Air.

At each study site, we collected water samples to analyze dissolved organic matter (DOM) composition, nutrient concentrations (nitrogen (N) and phosphorous (P) species), major cations and anions, and water isotopes ($\delta^{18}O$ and $\delta^{2}H$, or deuterium). We also conducted in situ measurements of water temperature, specific conductivity, and pH at each study using a YSI Professional Plus multi-parameter meter (YSI, Inc., Yellow Springs, Ohio). At all lakes, lake surface measurements were collect at a depth of 0.25 m. At a subset of lakes in GAAR, we measured temperature, specific conductivity, and pH at one-meter increments from the lake surface down to 20 m.
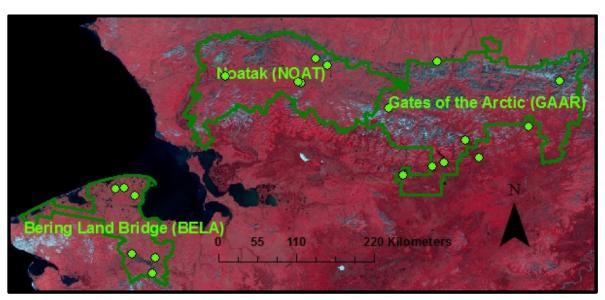

Figure 1. Map of large lake study sites in three NPS park units of Arctic Network. See the Appendix for detailed locations of lakes.

Table 1. Study sites from 2013-2014 pilot studies in the Arctic Network.

Site Name	Sampling Date	Lat (°N)	Long (°W)
Bering Land Bridge National Preserve			
Devil Mountain Lake	6/22/13	66.40362	-164.48818
Imuruk Lake	6/21/13	65.58905	-163.18683
Kuzitrin Lake	6/21/13	65.38450	-163.21787
Lava Lake	6/21/13	65.58996	-163.90928
Upper Killeak Lake	6/23/13	66.32813	-164.10563
White Fish Lake	6/22/13	66.37863	-164.74520
Gates of the Arctic National Park			
Iniakuk Lake	6/26/14	67.12570	-153.20834
Kurupa Lake	8/6/14	68.35879	-154.60695
Lake Matcharak	6/26/14	67.74715	-156.21262
Lake Selby	8/7/14	66.89298	-155.65584
Nutuvukti Lake	8/7/14	67.01337	-154.73245
Summit Lake	8/8/14	68.07008	-150.47092
Takahula Lake	6/26/14	67.35014	-153.66048
Walker Lake	8/7/14	67.06375	-154.34215
Wild Lake	6/26/14	67.50282	-151.57256
Noatak National Preserve			
Desperation Lake	9/16/13	68.33031	-158.74584
Feniak Lake	9/16/13	68.24775	-158.31337
Lake Kangilipak	9/16/13	68.00064	-159.15975
Lake Narvakrak	6/27/13	67.99990	-161.72104
Okoklik Lake	9/16/13	68.01392	-159.27007

Dissolved organic matter composition

DOM was characterized for dissolved organic carbon (DOC) concentration and optical properties (ultraviolet-visible (UV) absorbance) at the U.S. Geological Survey organic carbon laboratory in Boulder, CO. DOC concentrations were determined using an O.I. Analytical Model 700 TOC analyzer via the platinum catalyzed persulfate wet oxidation method (Aiken et al. 1992).

We used several approaches for analyzing and reporting the optical properties of chromophoric DOM (CDOM). Decadal UV-Visible absorbance (A) was measured on bulk DOC samples before lyophilization at room temperature using a quartz cell with a path length of 1 cm on an Agilent Model 8453 photo-diode array spectrophotometer. The Naperian absorption coefficient at 254 nm (α_{254}) has been shown to serve as a proxy for both DOC concentration and $\Delta^{14}C$-DOC in the YRB system (Spencer et al. 2009; O'Donnell et al. 2012, 2014; Aiken et al. 2014). We determined specific UV absorbance (SUVA$_{254}$) on HPOA isolates by dividing the decadal absorption coefficient at $\lambda = 254$ nm (A_{254}) by DOC concentration. SUVA$_{254}$, which is typically used as an index of DOC aromaticity (*Weishaar et al*., 2003), is reported in units of L mgC m^{-1}. Weishaar et al. (2003) also showed that UV absorbance values can be influenced by the presence of Fe. For bulk DOC samples containing iron, we applied correction factors based on experimental work by Poulin et al. (2014),

3

who observed a significant positive correlation between A_{254} and the concentration of Fe^{3+}, reflected by the equation $A_{254-corrected} = A_{254-measured}-0.0687*[Fe^{3+}]$ ($R^2 = 0.98$; $P < 0.0001$; n = 22). Using this relationship, we corrected A_{254} for samples where we measured total Fe concentration.

Nutrients, cations, and anions

Samples collected for nutrient, cation, and anion analysis were analyzed at the Cooperative Chemical Analytical Laboratory (CCAL) at Oregon State University in Corvallis, OR (website: *ccal.oregonstate.edu*). Unfiltered water samples were analyzed for total nitrogen (TN) and total phosphorous (TP) by persulfate digestion (Ameel et al. 1993) followed by colorimetric analysis on a Technicon Auto-Analyzer II (Seal Analytical, Mequon, Wisconsin). Total dissolved nitrogen (TDN) and phosphorous (TDP) were also determined using the persulfate digestion method on filtered water samples. Nitrate (NO_3^-) + nitrite (NO_2^-) were determined following the cadmium reduction method, and ammonia (NH_3) was determined following the phenate method. Orthophosphate, or soluble reactive phosphorous (SRP), was determined using the ascorbic acid method. Calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+) were analyzed using flame atomic absorbance spectroscopy on a Shimadzu AA-7000. Bromide (Br^-), chloride (Cl^-), and sulfate (SO_4^{2-}) were analyzed on a Dionex 1500 ion chromatograph.

Water isotopes

Stable isotopes of oxygen and hydrogen measured using Wavelength-Scanned Cavity Ringdown Spectroscopy on a Picarro L2120i (Sunnyvale, California) at the U.S. Army Cold Regions Research and Engineering Laboratory's (CRREL) Alaska Geochemistry Laboratory on Fort Wainwright, Alaska. Each standard and sample was injected into the analyzer for seven separate analyses. Results from the first four injections were not used to calculate the stable isotope values to ensure there was no internal system memory. The mean value from the final three sample injections was used to calculate the mean and standard deviation value for each sample. Values are reported in standard per mil notation. Repeated analyses of five internal laboratory standards representing a range of values greater than the samples analyzed and analyses of SMOW, GISP, and SLAP standards (International Atomic Energy Agency; http://www.iaea.org) were used to calibrate the analytical results. Based on thousands of these standards analyses and of sample duplicate analyses we estimate the precision is <0.2‰ for δ18O and <0.5‰ for δD.

Results

We observed thermal stratification at four lakes in GAAR, based on vertical temperature profiles measured in June 2014 (Figure 2a). Epilimnion temperatures ranged from 10 to 13 °C, and hypolimnion temperatures ranged from 4 to 8 °C. The depth of the metalimnion ranged from 6 to 8 m below the lake water surface. Prior work by LaPerriere et al. (2003) suggested that both Lake Matcharak and Takahula Lake are both dimictic (directly stratified in summer, inversely stratified in winter, and mix freely in spring and fall; Wetzel 1983). Specific conductivity values varied across lakes, with the highest values in Wild Lake (> 350 µS cm^{-1}) and lowest values in Lake Matcharak (~250 µS cm^{-1}). In Wild Lake and Lake Matcharak, specific conductivity increased slightly with depth. pH values were variable across lakes and with depth (Figure 2c). The highest pH values were measured in Takahula Lake, ranging from 8.15 to 8.35. The lowest pH values were measured in Wild Lake, ranging from 7.8 to 7.9. pH generally decreased with depth, except for in Wild Lake. The high pH and specific conductivity value in these GAAR lakes likely reflect weathering of carbonate parent material within the catchments (Meybeck *et al.* 1989).
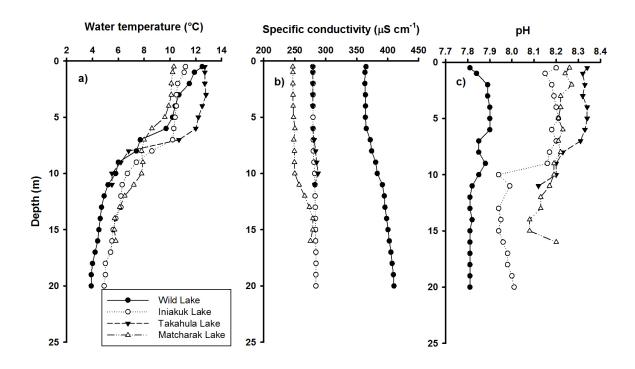
Figure 2. Vertical profiles of lake water temperature (panel a), specific conductivity (b), and pH (c) at four lakes in GAAR. All measurements were made on June 26, 2014.

Mean DOC concentration (± standard error) averaged 5.8 ± 3.8, 3.6 ± 1.6, and 5.2 ± 3.1 mgC L^{-1} in BELA, GAAR, and NOAT, respectively. We measured the highest DOC concentration in White Fish Lake (BELA; 12.3 mgC L^{-1}) and the lowest concentration in Walker Lake (GAAR; 1.3 mgC L^{-1}). In general DOC concentrations in this study fall within the observed range for Arctic tundra and alpine

ecosystems (1-5 mgC L-1; Schlesinger and Melack, 1981). DOC concentrations in large lakes of ARCN were significantly correlated to UV absorbance at 254 nm (Figure 3). This relationship has been observed in other studies focused on optical properties of DOM in high-latitude rivers (O'Donnell *et al*. 2012), and highlights the utility of in situ monitoring of optical properties to serve as a proxy for DOC concentration (e.g. Spencer *et al*. 2007). $SUVA_{254}$ values averaged 2.6 ± 0.1 across the 20 large lakes in ARCN. The highest $SUVA_{254}$ value was observed in White Fish Lake (3.5 L mgC^{-1} m^{-1}), indicating the presence of considerable aromatic carbon in the water (Weishaar *et al*. 2003). The lowest $SUVA_{254}$ value was observed in both Walker Lake and Lake Matcharak (1.5 mgC^{-1} m^{-1}), suggesting that aliphatic compounds dominate the DOM pool in these lakes.
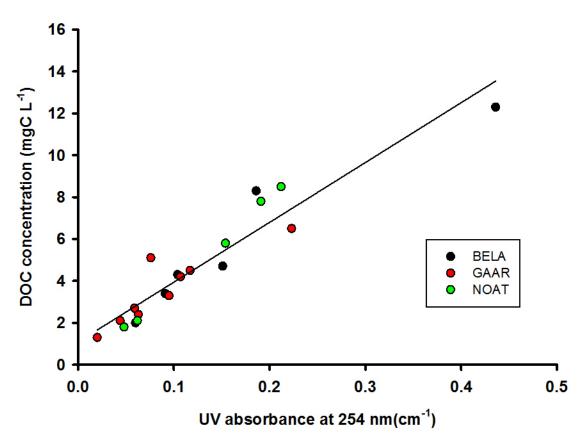
Figure 3. Linear regression relating DOC concentration and UV absorbance at 254 nm, described by the equation $y = 28.6x + 1.1$ ($R^2 = 0.90$, $P < 0.001$).

Nutrient concentrations were very low in most large lakes across the ARCN park units (data not shown). Inorganic nitrogen concentrations were generally at or below detection limits. The only lakes where ammonia concentrations were above detection limits were in BELA, with concentrations ranging from 19 to 135 μgN L^{-1}. The sum of nitrate and nitrite was also low, with the highest values observed in Walker Lake (190μgN L^{-1}) and Iniakuk Lake (141 μgN L^{-1}). Orthophosphate concentrations were below detection in every lake except White Fish Lake (6 μgP L-1). In general, these observations show that most lakes in ARCN are oligotrophic.

6

Base cation concentrations varied, both in amount and composition, across the three ARCN park units (Figure 4). Mean Ca2$^+$ concentration was highest in GAAR, averaging 28.4 ± 6.2 mg L^{-1}, and lowest in NOAT, averaging 7.9 ± 1.0 mg L^{-1}. The high proportion of Ca^{2+} relative to other base cations is likely due to the presence of calcareous rocks with lake catchments, as documented by LaPerriere *et al.* (2003). Sodium concentrations were generally low (<10 mg L^{-1}) across large lakes, except for White Fish and North Killeak Lakes, which averaged 54.2 and 161.9 mg L^{-1}, respectively. Potassium accounted for a very low proportion of all base cations.
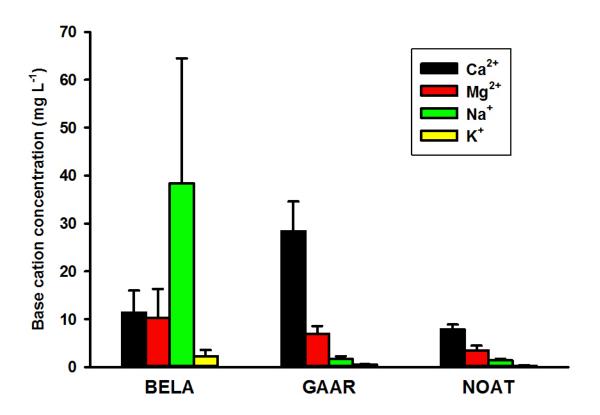
Figure 4. Mean base cation concentration across BELA, GAAR, and NOAT park units. Error bars represent one standard deviation. Ca^{2+} = calcium, Mg^{2+} = magnesium, Na$^+$ = sodium, and K$^+$ = potassium.

Anion concentrations were also variable across large lakes of the Arctic Network (Figure 5). Chloride concentrations were highest in BELA, averaging 76 ± 54 mg L^{-1}, compared to GAAR and NOAT. The high Na$^+$ and Cl$^-$ concentrations in BELA may be driven in part by the volcanic deposits present in the maar lake basins (e.g. North Killeak Lake, White Fish Lake); high Na$^+$ and Cl$^-$ concentrations have been observed in other maar lakes (Armiento *et al.* 2008). SO$_4^{2-}$ concentrations were highest in GAAR lakes, averaging 10 ± 3 mg L^{-1}, compared to BELA and NOAT. This variation in SO$_4^{2-}$ concentration is likely due to spatial variation in parent material, particularly the extent of shale (LaPerriere *et al.* 2003).
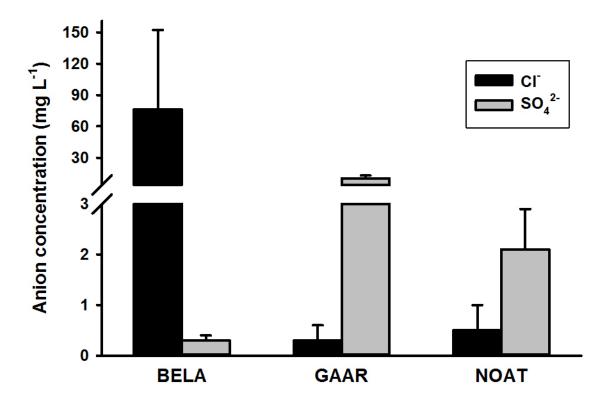
Figure 5. Mean chloride and sulfate concentrations across three ARCN park units.

We observed a significant positive correlation between ^{2}H and [18]O in large lakes of BELA and NOAT (Figure 6). We did not observe any clear patterns of water stable isotopes between NPS park units. Water stable isotope patterns are influence by many factors, including latitude, temperature, proximity to coastal storms, and the relative influence of snow vs. rain vs. groundwater.

All data reported here can be accessed through the NPS Integrated Resource Management Applications website at https://irma.nps.gov/App/Reference/Profile?code=2224786.

Figure 6. Linear regression between ^{2}H and ^{18}O stable isotopes, described by the equation $y = 6.66x - 20.52$ ($R^2 = 0.88$, $P < 0.0001$).

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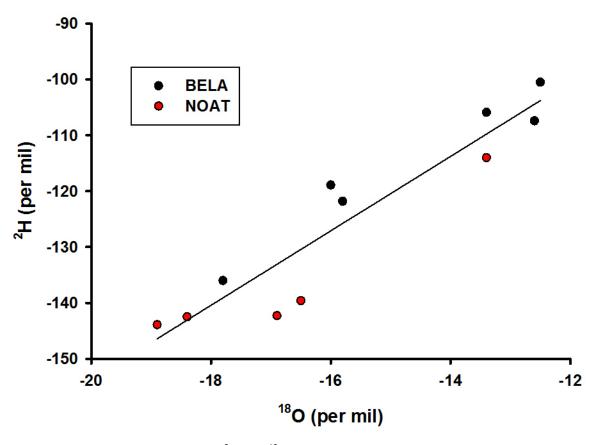Aiken, G. R., R. G. M. Spencer, R. G. Striegl, P. F. Schuster, and P. A. Raymond. Influences of glacier melt and permafrost thaw on the age of dissolved organic carbon in the Yukon River basin. *Global Biogeochemical Cycles,* doi:10.1002/2013GB004764.

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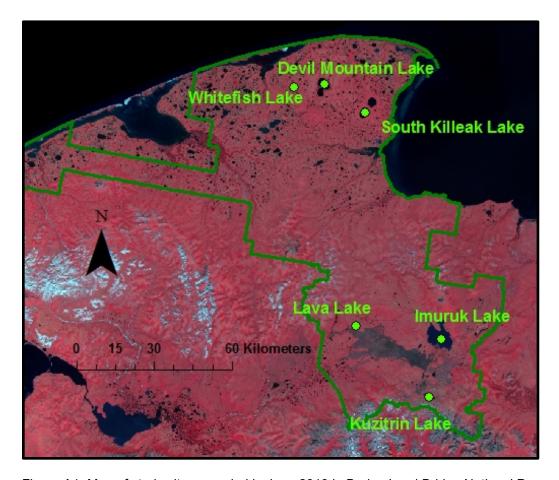
Appendix

Bering Land Bridge National Preserve

Figure A1. Map of study sites sampled in June 2013 in Bering Land Bridge National Preserve.

Devil Mountain Lake

Devil Mountain Lake is a largest maar lake in the world, located in the north-central region of the Bering Land Bridge National Preserve. It formed during the late Pleistocene (~17,500 year before present (BP)) during a period of volcanic eruptions, when magma interacted with thick, ice-rich permafrost (Beget *et al*. 1996). This process resulted in a series of massive steam explosions, which caused the development of craters that eventually filled with water and became a lake. Upland slopes have water-saturated, acidic, loamy soils with thick organic-soil horizons that support tussock tundra vegetation. Early successional forbs and alder-willow shrubs dominate the margin of the lake and associated beaches.

Figure A2. Picture of Devil Mountain Lake study site, sampled on June 22, 2013.

Imuruk Lake

Imuruk Lake is a large lake situated along the northern border of the Imuruk Lava flows, which occurred primarily in the late Pleistocene and early Holocene. The lava flows are largely barren with little soil development and only scattered forbs and lichen. Lake substrate is a mixture of volcanic sediments and muddy lacustrine deposits consisting of organic-rich limnic material.

Figure A3. Picture of Imuruk Lake study site, sampled on June 21, 2013.

Kuzitrin Lake

Kuzitrin Lake is situated in the Bendeleben Northern Foothills ecological subsection, where geology is characterized by colluvial deposits and outcrops of igneous and non-carbonate metamorphic rocks. It is large, oblong lake with clear water, indicating oligotrophic conditions. Lake substrate is gravelly sand. Along lake margins, sand is colonized by a small green moss. Birch and willow shrubs are the dominant vascular plants near the lake. The Kuzitrin River drains to the south from Kuzitrin lake.

Figure A4. Picture of Kuzitrin Lake study site, sampled on June 21, 2013.

Lava Lake

Lava Lake is a large lake that borders the Imuruk Lake lava flows to the south. Barren lava rocks border the southern lake margin, and the lake substrate is commonly composed of these rocks. The rest of the basin is situated in the Imuruk Uplands ecoregion. The geology here is dominated by colluvium overlying volcanic basalt, and the basin is dominated by tussock tundra vegetation and shrubs.

Figure A5. Picture of Lava Lake study site, sampled on June 21, 2013.

North Killeak Lake

The North and South Killeak Lakes are maar lakes formed approximately 40,000 y BP. They are situated in the Devil Uplands ecological subsection (Jorgenson et al. 2001), as are the other large maar lakes (Devil Mountain Lake and White Fish Lake). The margins along the North Killeak lake are characterized by steep banks, composed of fine volcanic sediments. Vegetation in the basin is dominated by tussock tundra.

Figure A6. Picture of Killeak Lake study site, sampled on June 23, 2013.

White Fish Lake

White Fish Lake is another large maar lake that formed 100,000 to 200,000 y BP. Upland slopes have saturated, acidic, loamy soils with thick organic-soil horizons that support tussock tundra vegetation. Early successional forbs and alder-willow shrubs dominate the margin of the lake and associated beaches. A mid-order stream flows in to the lake from the south. During sampling, we observed large amounts of suspended sediments in the water.

Figure A7. Picture of White Fish Lake, sampled on June 22, 2013
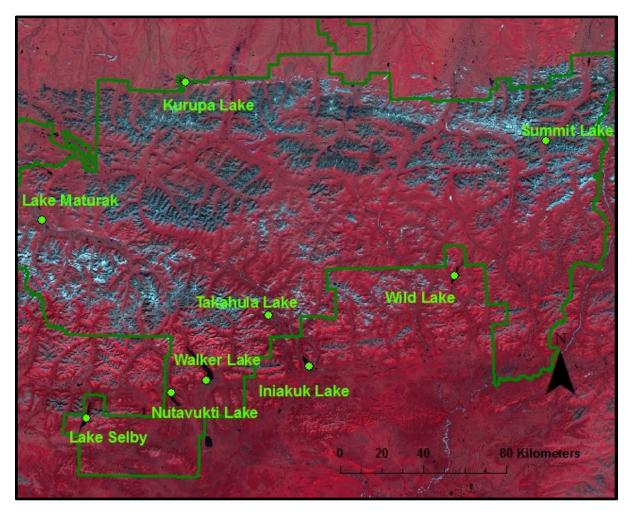
Gates of the Arctic National Park

Figure A8. Map of large lake study sites in Gates of the Arctic National Park, sampled in June and August 2014.

Iniakuk Lake

Iniakuk Lake (no picture) is a large lake situated in a broad valley just south of the park boundary.

Kurupa Lake

Kurupa Lake is a pristine large lake in the northern foothills of the Brooks Range. The lake is in the Etivluk Foothills ecological subsection (Boggs & Michaelson, 2001), and the lake resides in a mountain valley just south of the rolling tundra to the north. The water is very clear and the lake substrate is variably sized gravel. Vegetation in the catchment is dominated by tussock tundra and short shrubs.

Figure A9. Picture of Kurupa Lake study site sampled on August 6, 2014.

Lake Matcharak

Lake Matcharak is a large alpine lake situated in the upper Noatak River basin. Vegetation in the catchment is dominated by moist and wet tundra and short shrubs (LaPerriere et al. 2003).

Figure A10. Picture of Lake Matcharak, sampled on August 6, 2014 (picture by Greta Burkhart).

Lake Selby

Lake Selby is a large lake located in the southwestern part of GAAR in the Kobuk Lowlands – Forested ecological subsection. Lake Selby is hydrologically connected to Narvak Lake at a narrow nick-point in the landscape. The lake substrate is rocky with a mixture of coarse and medium sand. A dense alder shrub canopy lines the shoreline with some willows. Black and white spruce dominate forest cover in the uplands.

Figure A11. Picture of Lake Selby study site sampled on August 7, 2014.

Nutuvukti Lake

Nutuvukti Lake is a large lake located in the Kobuk Lowlands – Forested ecological subsection. The catchment is dominated by white and black spruce forests, and the lithology is likely dominated by glacial deposits. Lake water is clear, and sediments are comprised of coarse sand and small gravel. There is a large fen to the northeast of the lake that may be hydrologically connected to the Reed River.

Figure A12. Picture of Nutuvukti Lake study site sampled on August 7, 2014.

Summit Lake

Summit Lake is an alpine lake in the Thibodeaux Noncarbonate Mountains ecological subsection in the upper Itkillik/Oolah valley. There is little to no soil development in this subsection, and the topography includes rocky ridges and upper valley slopes. At lower elevations near the lake, vegetation is comprised dwarf shrubs and lichens. We observed submerged mosses and aquatic macrophytes in the littoral zone.

Figure A13. Picture of Summit Lake study site sampled on August 8, 2014.

Takahula Lake

Takahula Lake is situated in a mountain valley in the Alatna Mountain Valley ecological subsection. Lake sediments appear to be a mixture of rocks and coarse sand. Vegetation in the catchment is dominated by short shrubs and white/black spruce in the valley bottom.

Walker Lake

Walker Lake is a large and deep lake located in the Kobuk Mountain Valley ecological subsection. Closed and open spruce stands dominated catchment vegetation. Lake sediments are a mixture of coarse and medium sand, with lots of small gravel and rocks.

Figure A14. Picture of Walker Lake sampled on August 7, 2014.

Wild Lake

Wild Lake is a large lake in the Koyukuk Mountain Valley ecological subsection. Tobin Creek enters Wild Lake from the north, and the Wild River drains from the lake to the south. The catchment is a broad mountain valley, with dwarf shrubs in the upland slopes and white spruce at lower elevations.
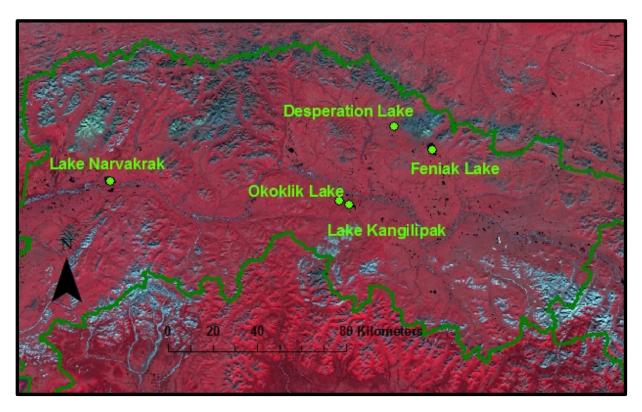
Noatak National Preserve

Figure A15. Map of five large lakes sampled in 2013 in Noatak National Preserve.

Desperation Lake

Desperation Lake is a large lake in the Avingyak Glaciated Upland ecological subsection of the upper Noatak River basin. This region is a gently rolling upland area with glacial drift associated with the Itkillik glaciation. Soils are generally wet with thick organic horizons, and vegetation is dominated by tussock tundra forms. Lake water is very clear. Sediments are composed of rocks and gravel, with little to no algal biofilm.

Figure A16. Picture of Desperation Lake, sampled on September 16, 2013.

Feniak Lake

Feniak Lake is also in the Avingyak Glaciated Upland ecological subsection of the upper Noatak River basin. Vegetation along the lake margin is typical of alpine tundra, with mosses, willows, sedges, and some lichen. The lake water is very clear, indicating oligotrophic conditions. The substrate is a mixture of rocks, gravel, and coarse sand.

Figure A17. Picture of Feniak Lake, sampled on September 16, 2013.

Lake Kangilipak

Lake Kangilipak is in the Aklumayuak Glaciated Uplands ecological subsection, a region characterized by rolling hills and covered by glacial drift associated with the Itkillik glaciation. Permafrost is continuous in this region, and there are some large retrogressive thaw slumps in glacial deposits in the region. Vegetation within the basin is tussock tundra, with dwarf shrubs along the lake margins. Lake substrate is fine, small gravel and coarse sand. During our sampling, we observed a think layer of algal biofilm on gravel substrate.

Figure A18. Picture of Lake Kangilipak, sampled on September 16, 2013.

Lake Narvakrak

Lake Narvakrak is in the Middle Noatak Uplands ecological subsection, draining a watershed comprised of glacial till, bedrock ridges, and alluvial terraces. Moist-to-wet soils support considerable organic accumulation. Permafrost in the region has low to moderate ground ice content. Lake water is dark brown, indicating high organic matter content. The lake margin was densely colonized by sedges and willows.

Figure A19. Picture of Lake Narvakrak, sampled on June 27, 2013.

Okoklik Lake

Okoklik Lake is also in the Aklumayuak Glaciated Uplands ecological subsection. It is a large, oblong-shaped lake situated in a rolling tundra basin. The lake may be more productive than other lakes in the region, with a ubiquitous algal biofilm covering the rocky substrate. Vegetation along the lake margin is dominated by sedges and willows, with shrub-rich tundra in the uplands.

Figure A20. Okoklik Lake study site, sampled on September 16, 2013.

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